Thermocouples and *realistic* expectations

The thermocouple is probably the most commonly used sensor in data acquisition. The principle of the thermocouple is fairly straightforward. Whenever two dissimilar metals are in contact, a voltage (referred to as the Seebeck voltage) is produced, and this voltage is related to the temperature at the point of contact or junction. Though any two metals can be used to form a thermocouple, a small number of configurations have been standardized upon. These have been designated by letters. The most commonly used thermocouples include the J, K, and T types with R and S also being popular in high temperature (>1200 °C) applications.

First, Construct an Error Budget

There are a few characteristics of thermocouples that either limit or complicate their use. These characteristics sometimes lead data acquisition customers to design improper systems. However a much more common disappointment in thermocouple applications stems from designers unrealistic expectations of a properly designed system. Prior to selecting the thermocouple as your sensor of choice, you should determine the absolute temperature accuracy you require. From there, you can construct an *error budget* for the system you propose, and make sure your system is up to the task. If not, you may want to consider other system components or even an alternate temperature sensor. An error budget equation is shown below.

$$\text{Error in } ^\circ\text{C} = \text{TC}_{\text{error}} + \text{CJC}_{\text{error}} + \text{A/D}_{\text{error}} + \text{Noise}$$

where TC_{error} is the inherent error of the thermocouple,
$\text{CJC}_{\text{error}}$ is the error caused by the cold junction compensation
$\text{A/D}_{\text{error}}$ is the error in the A/D system
Noise is the error caused by RFI, EMI and other environmentally induced noise

TC_{error} --Thermocouple error

The largest and most commonly overlooked cause of error in thermocouple systems is the thermocouple itself. This error is depicted by TC_{error} in the error budget. Typical errors are in the range of ±1°C to ±2.2°C at room temperatures with errors becoming as large as ±7.5°C at 1000°C. The table in the next column shows typical errors for a few common thermocouples. Notice that even the special, high accuracy versions may have significant inherent errors.

$\text{CJC}_{\text{error}}$ --Cold-Junction Compensation Error

Another complication of all thermocouple system is the unavoidable cold-junction thermocouple. In every system, the thermocouple wire has to be connected to the A/D board at some point. The two points of connection are also thermocouples. Today's data acquisition systems remove this error by measuring the temperature at the system connection point, determining the cold-junction error, and subtracting the error voltage in software. Most systems use a semiconductor temperature sensor to measure the CJ temperature. These sensors have typical errors on the order of 0.5°C, with worst case errors of 1°C. Unfortunately, a 1°C error in the cold-junction compensation, leads to roughly a 1°C error in the final temperature measurement. This error is designated as $\text{CJC}_{\text{error}}$ error budget equation.

type	metals	Seebeck Voltage (at 20°C)	Standard* accuracy	Enhanced* accuracy
J	Iron/ Constantan	51 uV/°C	±2.2°C or ±0.75%	±1.1°C or ±0.4%
K	Nickel-Chromium/ Nickel-Aluminum	40 uV/°C	±2.2°C or ±0.75%	±1.1°C ±0.4%
T	Copper/ Constantan	40uV/°C	±1.0°C or ±0.75%	±.5°C or ±0.4%
R	Platinum Platinum-13% Rhodium	7uV/°C	±1.5°C or ±0.25%	.±6°C OR ±0.1%
S	Platinum Platinum-10%Rhodium	7uV/°C	±1.5°C or ±0.25%	±.6°C OR ±0.1%

* use whichever accuracy spec is greater. Enhanced accuracy versions not available from all vendors.

$\text{A/D}_{\text{error}}$ --A/D System Error

Most A/D systems have basic input ranges of either ±5V or ±10V full scale. In addition, systems suitable for thermocouple monitoring will also have selectable input gains of 100-500. For example, our CIO-DAS08 12-bit A/D board set for ±5V

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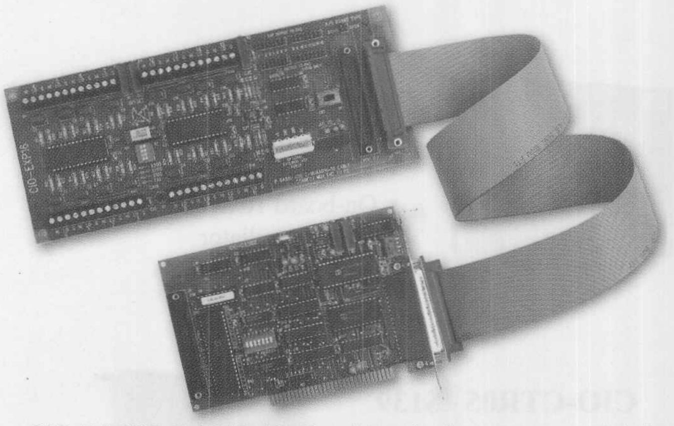


The CIO-DAS08 & EXP-16 Combine to form a powerful, low cost, 16-channel thermocouple monitoring system.

(thermocouple..., continued from page 12)

full scale, configured with a CIO-EXP16 set with a gain of 100 provides a full scale input range of 50mV (5V full scale divided by 100 equals 50 mV). This is sufficient range to measure all but the highest temperature on most thermocouple types. This equation below will determine the overall resolution of the system in uV.

$$\text{Resolution} = (\text{Full scale range}) / 2^{\text{bits of resolution}}$$

$$\text{Resolution} = 50\text{mV} / 2^{12}$$

$$\text{Resolution} = 12\ \text{uV}$$

So, this system provides 12 uV resolution. Assuming a K type thermocouple, the chart above provides a output scale factor of 40 uV/°C. The following equation are used to calculate the system's resolution in °C.

$$\text{Resolution }°\text{C} = (\text{Resolution in uV}) / \text{TC scale factor}$$

$$\text{Resolution }°\text{C} = (12\ \text{uV/bit}) / (40\ \text{uV}/°\text{C})$$

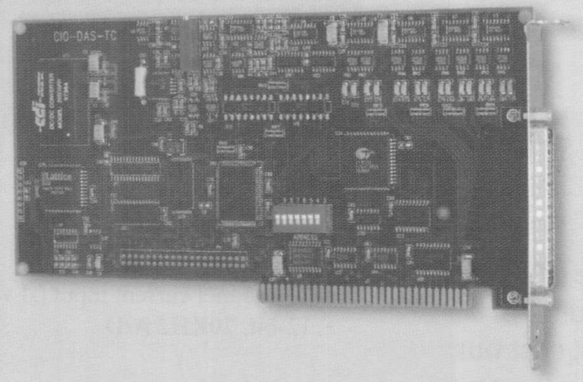
$$\text{Resolution }°\text{C} = 0.3\ °\text{C / bit}$$

This system provides 0.3 °C resolution with a K type thermocouple.

Moving back to the CIO-DAS08, CIO-EXP16 example system, each board has an error specification of ±0.01% ±1 bit. Simply adding these two error specifications together provides an unlikely, but worst case system error of ±0.02% ±2 bits. Notic that ±0.02% is equivalent to one part in 5000 and is roughly equivalent to a 1 bit error (1 part in 4096). A realistic worst case estimate of the CIO-DAS08/EXP-16 system's error specs is ±3 bits.

Using the scale factor determined earlier of 0.3°C/bit and the total system error of ±3 bits, the $\text{A/D}_{\text{error}}$ component of the error budget becomes ±0.9°C (0.3°C/bit x ±3 bits). On the surface this may look like a large error, and you might be tempted to opt for higher gain (which would limit your full scale input range), or perhaps a 16-bit A/D board. However, keep in mind that the ±1°C is smaller than the error specification of most thermocouples and is similar in size to the CJC error. If *absolute* accuracy is your goal, upgrading to a higher resolution A/D board, a higher performance expansion board or switching to a specialize thermocouple board such as the ComputerBoards CIO-DAS-TC will help, but may not help enough to provide the absolute accuracy required. If relative accuracy is the goal, upgrading the A/D board will provide substantial benefits. The absolute versus relative accuracy topic is discussed later in this article, but first one final error source must be addressed.

CIO-DAS-TC $599



Features

- 16 Thermocouple inputs
- J, K, E, T, R, S, B, support
- On-board microprocessor converts input into °C or °F reducing PC workload

ComputerBoards offers a wide assortment of thermocouple and temperature measurement solutions. Please call us to discuss the best system for your application!

Temperature Input Specifications

TC	Range	Resolution
J	-200 to +750 °C	± 0.1 °C
K	-200 to +1,250 °C	± 0.2 °C
E	-200 to +1,000 °C	± 0.1 °C
T	-200 to +400 °C	± 0.06 °C
R	0 to +1,768 °C	± 0.2 °C
S	0 to +1,450 °C	± 0.2 °C
B	+400 to +1,700 °C	± 0.2 °C

(the above resolutions are at 25 samples/sec)

Cold-junction error	± 0.5 °C	at 25°C
	± 1.2 °C	0 to 70°C

Software Description

Includes a complete data display and logging application (built in Visual Basic with source code supplied). Also includes *Insta*Cal™, installation, calibration and test software. Supported by UniversalLibrary™ (provides programming language support for all DOS and Windows languages).

CIO-TERM-TC Screw Terminal board $99

The CIO-TERM-TC provides an isothermal block and cold-junction sensor and is recommended for use with the DAS-TC board. The CIO-TERM-TC connects to the CIO-DAS-TC via a C37FF-# series cable.

Noise

Thermocouples are often used in harsh, noisy industrial settings. In these installations there may be significant EMI, RFI and other electronic noise sources. While you may see some jitter in your temperature measurements in the laboratory, an industrial application (especially if the TC is a long distance from the input board) may observe many degrees of high frequency noise induced sample jitter.

Most Noise is Easily Removed

Though thermocouple time constants are slow, (as long as a second or more) most analog input boards use high speed A/D converters, and these converters are affected by high frequency noise, even when sampling at low sample rates. If your temperature readings show wider than expected fluctuations, this high frequency noise is likely the cause. The simplest solution is to use the average of a number of samples. Most data acquisition systems easily have the capability to sample at hundreds or even thousands of samples per second. This allows you to take averages of many samples and yet still maintain an update rate of considerably less than a second. We recommend you try at least 10 samples per average as a first try. However, you may choose to use more samples to reduce the noise impact even further.

Putting Together All the Components

At this point all the error components are defined and the actual error specification is determined by plugging the numbers into the original error budget equation. The worst case error specification for our example system is shown below.

$$\text{Error in °C} = TC_{error} + CJC_{error} + A/D_{error} + \text{Noise}$$

TC_{error} = ±1.1 °C (enhanced K type Thermocouple)

CJC_{error} = ±1.0 °C

A/D_{error} = ±0.9 °C

Noise = ±0.1 °C (assume enough samples are averaged to achieve this level)

Error = ±3.1 °C worst case error

Relative versus Absolute Accuracy

Until now, this article has focused on absolute accuracy. However, in many applications, absolute accuracy is not as critical as relative accuracy. It may not be important to know the exact temperature of the bearings in your engine, but it may be crucial to know when the temperature has gone up even a few degrees. In these cases, a thermocouple based system is an ideal solution. Though thermocouple and CJC errors may be a few degrees or more, these errors are typically constant and repeatable. In these cases, the additional cost of a high resolution A/D board may be easily justifiable. Referring to the original error budget equation, and making a conservative estimation that relative Thermocouple and CJC errors are one tenth the magnitude of their absolute errors provides:

$$\text{Relative Error} = TC_{error} + CJC_{error} + A/D_{error} + \text{Noise}$$

$$\text{Relative Error} = \pm 0.1°C + \pm 0.1°C + A/D_{error} + \text{Noise}$$

Again assuming enough sample averaging is done to keep the noise contribution to ±0.1°C, the equation becomes

$$\text{Relative Error} = \pm 0.3°C + A/D_{error}$$

Compare the ±0.3°C non A/D induced error to the CIO-DAS08/EXP-16's overall temperature resolution of ±0.3°C and error specification of ±3°C. In relative temperature measurements, the 12-bit resolution A/D system becomes the dominant error contributor. In these applications, a 16-bit resolution A/D system is a better choice. Replacing the 12-bit CIO-DAS08 with the 16-bit CIO-DAS802/16 increases A/D resolution by a factor of 16 to ±0.019°C per bit. Based on the A/D board nonlinearity specification of ±1.5 bits, its contribution to relative error is approximately ±.03°C (1.5 bits times 0.019). With a gain of 100 linearity of ±0.004% the expansion board makes the largest contribution to error. This is one part in 25,000 or roughly 3 LSBs at 16-bit resolution (or ±0.06°C). Combining both boards relative error contribution provides an A/D system error of ±0.09 °C (0.06°C + 0.03°C) or roughly ±0.1°C. Plugging this number into the Relative Error equation yields:

$$\text{Relative Error} = \pm 0.3\ °C + \pm 0.1\ °C = \pm 0.4\ °C$$

If relative temperature measurement is the goal, accuracies of better than 0.5°C are achievable. The ComputerBoards CIO-DAS-TC board (see data sheet to the left) is designed specifically for use with thermocouples. In addition to providing a high resolution, noise immune, integrating A/D converter, the board also provides an on-board microprocessor that performs all linearization and cold-junction compensation. Simply connect your thermocouples to the input of the board, and read your temperature directly in °C or °F.

If you have any questions regarding the suitability of the thermocouple for the measurement you're making, or how to best configure a system for your application, please call or email a ComputerBoards' technical support engineer. They will be happy to help you configure your system.